"Long Life" DC brush motor for use on the Mars Surveyor Program

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Abstract

DC brush motors have several qualities which make them very attractive for space flight applications. Their mechanical commutation is simple and lightweight, requiring no external sensing and control in order to function properly. They are extremely efficient in converting electrical energy into mechanical energy. Efficiencies over 80% are not uncommon, resulting in high power throughput to weight ratios. However, the inherent unreliability and short life of sliding electrical contacts, especially in vacuum, have driven previous programs to utilize complex brushless DC or the less efficient stepper motors. The Mars Surveyor Program (MSP'98) and the Shuttle Radar Topography Mission (SRTM) have developed a reliable "long life" brush type DC motor for operation in low temperature, low pressure CO_2 and N_2, utilizing silver-graphite brushes. The original intent was to utilize this same motor for SRTM's space operation, but the results thus far have been unsatisfactory in vacuum. This paper describes the design, test, and results of this development.

Introduction

This work was performed at the California Institute of Technology's Jet Propulsion Laboratory, under contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process or service by trade name, trademark, manufacturer, or otherwise does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory.

The Robotic Arm is part of the scientific and engineering payload for the Mars Surveyor Program (MSP'98) mission which will explore the South Pole of the Martian surface. It is a 2 meter long, semi-autonomous, 4 degree of freedom arm designed to dig in very hard soil of the seasonally receded CO_2 polar cap. The flight Robotic Arm is shown in Figure 1. The mission is scheduled for launch in January 1999 and will land on Mars in December, 1999.

Environments

During assembly, test, and flight of the Robotic Arm, the motors are subjected to a number of environmental conditions:

1. Operate in ambient air, up to 55% relative humidity (clean room functional checks).

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2. Operate in 8 Torr N_2 from -80 C to -10 C (system level testing).
3. Survive in vacuum (flight; cruise phase)
4. Operate in 8 Torr CO_2 from -80 C to -10 C (on Mars).

For SRTM, the main environmental challenge is to operate in a vacuum.

Background

The initial motor choice for the Robotic Arm was the Maxon RE016 motor which had been used successfully on the Mars Sojourner Rover. This 38 gram motor was an ironless core brush type DC with precious metal brushes, Neodymium-Boron-Iron magnets, oil-impregnated bronze bushings, and rotor mounted capacitor for arc suppression and long brush life. Maxon specifies a minimum operating temperature of -20 °C for this motor, which was not sufficient for the -80 °C Mars Sojourner Rover environment. The main modification was to delete the grease normally applied to the commutator. At temperatures below -60 °C, the grease could bond the delicate motor brushes to the commutator, resulting in a permanent failure due to bent motor brushes. A secondary problem was the bushing oil lost its effectiveness below -40 °C resulting in increased wear and current draw which reduced bushing life. The wear was judged to be acceptable, so no modifications were made to the bushings. Since the ironless core rotor has no inherent detent torque, an external magnetic detent had to be added in order to hold position when unpowered.

The Sojourner Rover primary mission required 100 meters of travel on Mars, in addition to 100 meters of testing. That amount of travel equals approximately 1 million motor revolutions. The "extended" mission of up to 1 Km on Mars would require a total of 5.4 million motor revolutions. Two motors were tested to 40 million revolutions (no-load, +20 °C , low pressure air) without failure, and two complete actuators were tested under load and start-stop conditions to 30 - 40 million revolutions at failure. Part of the testing was conducted at -70 °C in low pressure CO_2. Primary failure mode was conductive debris bridging the gaps in the commutator. These tests showed adequate life margin for the Sojourner mission.

Testing Maxon RE016 Motors for the Robotic Arm

Although the Maxon RE016 motors chosen for the Robotic Arm were nearly identical to the Sojourner motors, there were sufficient differences in the design and operating conditions which warranted further testing. The main difference was the requirement to operate the motors at their full rated 30 volts as opposed to Sojourner's conservative 15.5 volts. In addition, SRTM was required to operated at 28 volts in a vacuum as opposed to the 8 Torr CO_2 environment of Mars. Also, in the 2 years between the Sojourner and Robotic Arm programs, Maxon began offering ball bearings and a double-ended shaft on the RE016 motors. The ball bearings greatly improved performance below -40 °C (when lubricated with Braycote 604 for low temperature operation) and the double ended shaft simplified the incorporation of the magnetic detent and encoder.

RE016 Test Results

29 Maxon RE016 motors were tested under various conditions of air, vacuum, low-pressure CO_2, low-pressure N_2, and several methods of commutator lubrication. All of the testing was done between -70 °C and -80 °C. The new testing resulted in much lower life times (less than 10 million revolutions average) than was experienced in the earlier Sojourner Rover tests. Three separate failure modes were observed. The most common, which also was observed on the Sojourner tests, was rotor shorting due to conductive debris in the commutator slots. The second common failure mode was motor brush damage. The motor brushes and commutator would gall or micro-weld together, bending the delicate brushes out of contact with the commutator or breaking the brushes off entirely. The least observed (one or two times) failure was physical contact between the rotor and motor casing, resulting in an open circuit in the rotor winding. It is possible that operating the motors well outside of the limits specified by the manufacturer could have warped the rotor or that these motors were built with slightly smaller (but within tolerance) clearances which weren't enough for our temperature range.

Motor life Vs. atmospheric conditions for the Maxon motors are shown in Figure 2. This data includes Sojourner life tests. The chart only shows how long the motors lasted until failure, but does not indicate what type of failures were observed. Of the 5 motors in vacuum with unlubricated commutators, 100% exhibited damaged motor brushes. Of the 10 motors in CO_2 with unlubricated commutators, 60% had damaged brushes. Of the 5 motors in vacuum with lubricated commutators, 20% had damaged brushes. And of the 10 motors in CO_2 with lubricated commutators, there were no damaged brushes.

Figure 3 shows motor life vs. voltage. There is no clearly visible influence of voltage on motor life (with "life" given in terms of motor revolutions). Due to the large number of variables included in the testing, there is a large variation in the results which could easily mask any effects due to voltage. A factor of 2 or 3 difference could be hidden by the noise.

The Sojourner Rover Team, only a few weeks from launch, was somewhat alarmed by the new test results, but life looked adequate for at least completing the primary mission. With 6 wheels, the mission could even be accomplished if one motor failed. It was not practical at this late stage of the program to make any changes to Sojourners motors*.

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* The Sojourner Rover was still running with no indication of motor problems when the Lander communication link failed to transmit to Earth. Total travel on the surface of Mars was approximately 100 meters.

Requirements Re-examined
The life requirements for the Robotic Arm had been stated only in terms of the need to be able to dig a trench in Mars up to .5 M deep. This was converted into an equivalent life requirement in motor revolutions by looking at scoop volume and how many movements it would take to dig the required trench. The result was 10 million revolutions. The motor life should therefore be in the 30 to 100 million revolution range in order to have a comfortable margin. There was a definite mismatch between the required life and the test results. (In fairness to Maxon, it should be remembered that this motor was designed for atmospheric operation above -20 °C, and we were trying to make it run at -80 °C in vacuum and 8 Torr CO_2).

Decision to Use a Larger Motor

Early in the RE016 testing program, when the first indications of a problem were becoming apparent, an effort was launched to identify alternative motor designs and suppliers. The Cassini program had developed and qualified a brush-type DC motor for the engine gimbal actuator, which operated in vacuum. Although the size and configuration of the motor was not directly applicable to the Robotic Arm or SRTM, the success with silver-graphite motor brushes (SG54-27 from Superior Carbon) running on a copper commutator was encouraging.

A slightly larger motor was desirable from several standpoints. The higher torque would allow us to use a smaller gear ratio, thus reducing the number of motor revolutions needed to accomplish the mission. Higher power could also be utilized, allowing the mission to be completed in less time (the lander had more power available than the RE016 motors could use). A larger motor would have more room internally for larger motor brushes, increasing potential life. The only technical drawback was the increased mass (initially, the Robotic Arm mass budget was too tight to baseline heavier motors).

New Motor Options
The MVACS project evaluated the reliability and lifetime issues for the Robotic Arm. In addition to the requirement for longer life, the motors on the Robotic Arm represented single point failures, where failure of any one of the motors would result in total loss of the arm's capability to complete its tasks. Because of these critical issues, .3 kg of project contingency mass was added to the Robotic Arm mass budget so that the larger motors could be accommodated. Gear ratios on the elbow and shoulder elevation actuators were reduced by a factor of 5 by simply shortening the gearcase and omitting one stage of the planetary gearbox.

After the approval for the change, the effort was then focused on the formidable task of getting the motors delivered on time. We had only 3-4 months until the new motors were needed. The American Technology Consortium (ATC) proposed a custom designed 100 gram motor using a conventional iron-core rotor which would also provide inherent magnetic detent torque. With ATC's a good record of extremely rapid delivery on a Mars Pathfinder actuator, this became the new baseline approach. As a back-up option, JPL purchased stock Maxon RE025 graphite brush motors (130 grams) with an ironless rotor, which would have to be retrofitted with SG54-27 brushes, re-lubricated bearings, and external magnetic detent assembly.

ATC Motor Development Lessons Learned and Good Design Practice

There were many lessons learned during the development of the ATC motors. For a schedule-critical program such as the Robotic Arm, it is important to identify any long-lead-time items which may need design iteration, and try to develop a selection of designs in parallel instead of in series. One example is ordering and processing several candidate brush materials concurrently. Another example is the rotor core design, which is critical in obtaining the desired magnetic detent torque. The original design did not have enough detent and several weeks could have been saved by fabricating two or three core designs simultaneously, and selecting the one that best met the requirements.

Late in the program, we experienced an open circuit motor failure. Disassembly and inspection of the motor revealed a manufacturing defect. A service loop between the rotor windings and the commutator had inadvertently been potted taught against the windings; subsequent thermal expansions and vibrations had eventually broken the wire. To assure that this situation did not cause a flight failure, the flight mechanisms (which had passed acceptance tests at the time) had to be disassembled for inspection. Significant time and effort could have been saved if we had carefully inspected all rotors before assembly.

Unlike precious metal brushes, graphite brushes generate significant quantities of conductive debris, and the motors must be designed to accommodate it. Electrically conductive surfaces internal to the motor should be conformal coated wherever possible to minimize the possibility of shorting or grounding, and space should be provided within the endbell for the debris to safely accumulate.

Predictions of motor brush wear rate are not very accurate, and it is best to provide as much motor brush length as possible. A cantilevered leaf spring design was used for the MVACS motor; while this provided adequate life, a cartridge-type brush design would improve motor life significantly.

Testing the ATC Motors

Screening Tests

All motors were put through a screening test to check for early failures or defects. After two cycles between +80 C and -125 C (non-operating), the motors were run at various speeds at +80 C and -90 C. Motor current was charted whenever the motors were operated.

A variety of other tests were conducted to characterize the motors and provide data for selecting the best ones for flight. Magnetic detent torque and no-load speed were measured, minimum running voltage was tested, and friction torque was estimated from the measurements. Many of these measurement were made both by ATC and JPL. After the flight and spare motors were selected, dynamometer tests were conducted at JPL (also a duplicate of the ATC testing). Plots of Current Vs. Torque and Speed Vs. Torque for motor S/N 0039 (used for the flight shoulder elevation actuator) are given in Figures 4 and 5, respectively.

<u>Life Testing</u>

No-load tests of both the ATC and modified Maxon motors in air and 8 Torr CO_2 showed excellent life and reliability, in excess of 100 million revolutions with no failure. Extrapolating from the measured brush wear, it is estimated that the motors would last 300 to 500 million revolutions under no-load conditions. Complete mechanisms with ATC motors were cycled under high load in -70 °C, 8 Torr CO_2, resulting in lifetimes of 102 million, 62 million revolutions in ambient air, and 36 million revolutions at -70 C in 8 Torr nitrogen before the motor brushes wore out. There were some differences in the loading conditions of the tests, but they do not appear to be large enough to account for the factor of 3 difference between the CO_2 and nitrogen lifetimes. Although we tentatively attribute the life difference to the gas, we can not come to any solid conclusions on the basis of only one test.

Vacuum test results (for SRTM) were far less satisfactory. Only no-load tests were conducted at JPL. Results are generally described by several minutes to hours of smooth operation, followed by a sudden transition to high and variable current draw and motor brush wear-out after as little as 3 million revolutions. An alternative motor brush material (Superior Carbon SG59) appeared to perform somewhat better, with over 5 million revolutions of smooth operation before the high current phase, and wear-out in the 20 million revolution range. Interestingly, 3 completely stock RE025 motors with lubricated precious metal brushes were run for 21 million revolutions in vacuum at +20 °C without any problems.

Summary and Discussion

The fundamental limitation of lifetime for brush type DC motors is due to wear and lubrication at the brush/commutator interface. The materials for brushes, commutators and lubrication must be electrically conductive and be compatible with its intended environment (temperature and atmosphere).

Precious metal brushes require a wet lubricant to function properly. The usual lubricants developed for sliding electrical contacts can not function below -60 °C and have high outgassing rates in vacuum. Without wet lubrication lifetime is severely reduced, but adequate for the Sojourner Rover program. The presence of even a small amount of atmosphere was found to be extremely important to avoid immediate catastrophic failure of unlubricated precious metal brushes. It is possible that lubricants could be found or developed for precious metal brushes that would be compatible with low temperature and vacuum applications.

"Graphite" brushes are a sintered mixture of a conductive medium (copper or silver) and lubricating materials such as graphite, molybdenum disulfide, and a number of other proprietary compounds. One major advantage of this material is that it does not require a wet lubricant, and therefore can operate very cold. Conventional wisdom states that graphite needs moisture in order to function as a lubricant. Our testing showed that 8 Torr of dry CO_2 allowed the motor brushes to perform about as well as in moist air and one or two orders of magnitude better than in vacuum. These results are good news for Mars missions such as MVACS, not so good for SRTM which must operate in a vacuum. SRTM decided that the best solution for their program is to seal the actuators in an atmospheric environment.

Several other motor contact materials and processes are available. Unfortunately, our testing program could not be comprehensive due to schedule and cost pressures. Claims have been made for wear rates of one material in vacuum that are two or three orders of magnitude better than the test results at JPL. JPL's plan is to continue testing of this material and others in the next few months to determine the best material for Mars and space missions.

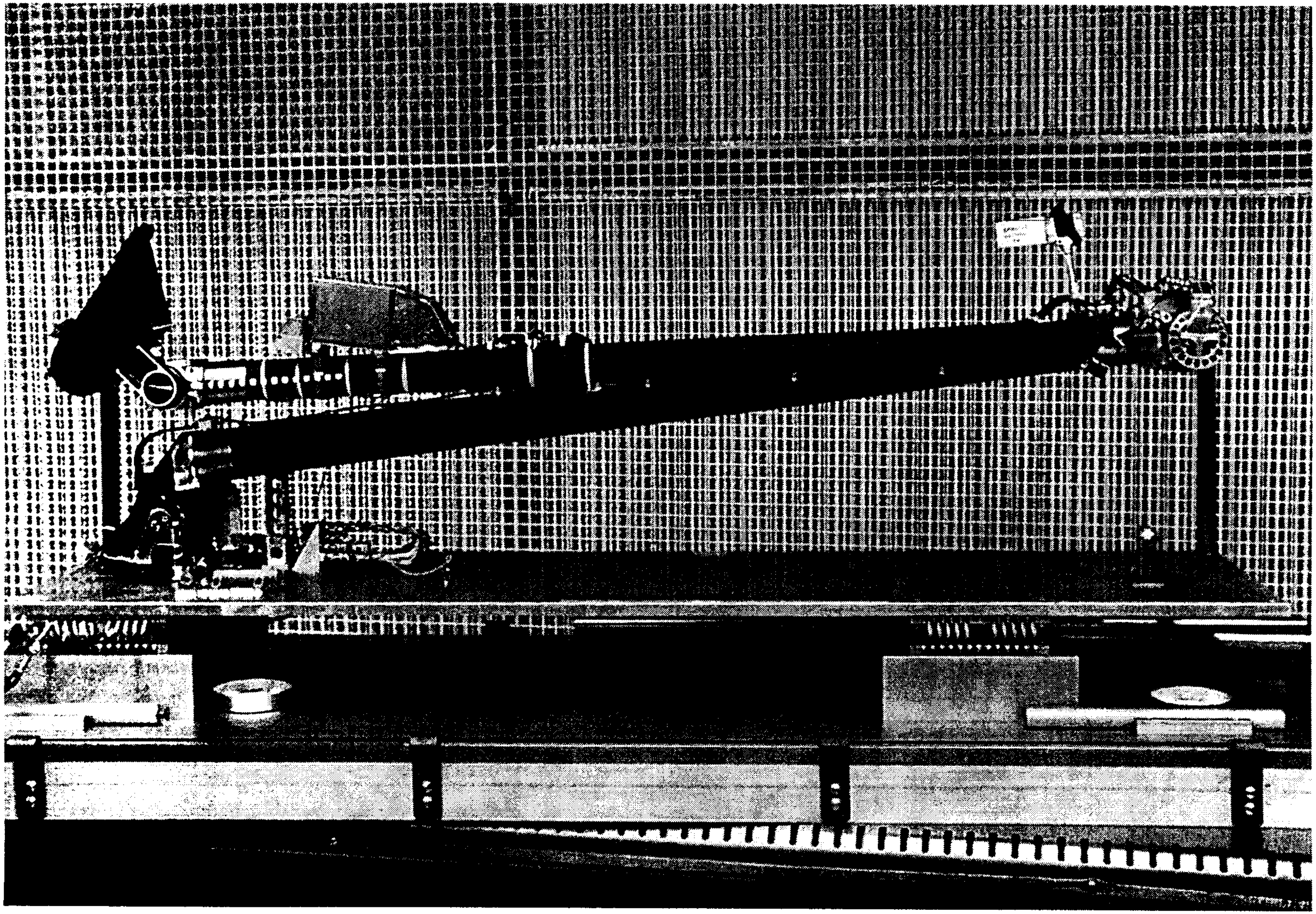

Figure 1. 1998 Mars Surveyor Program Robotic Arm.

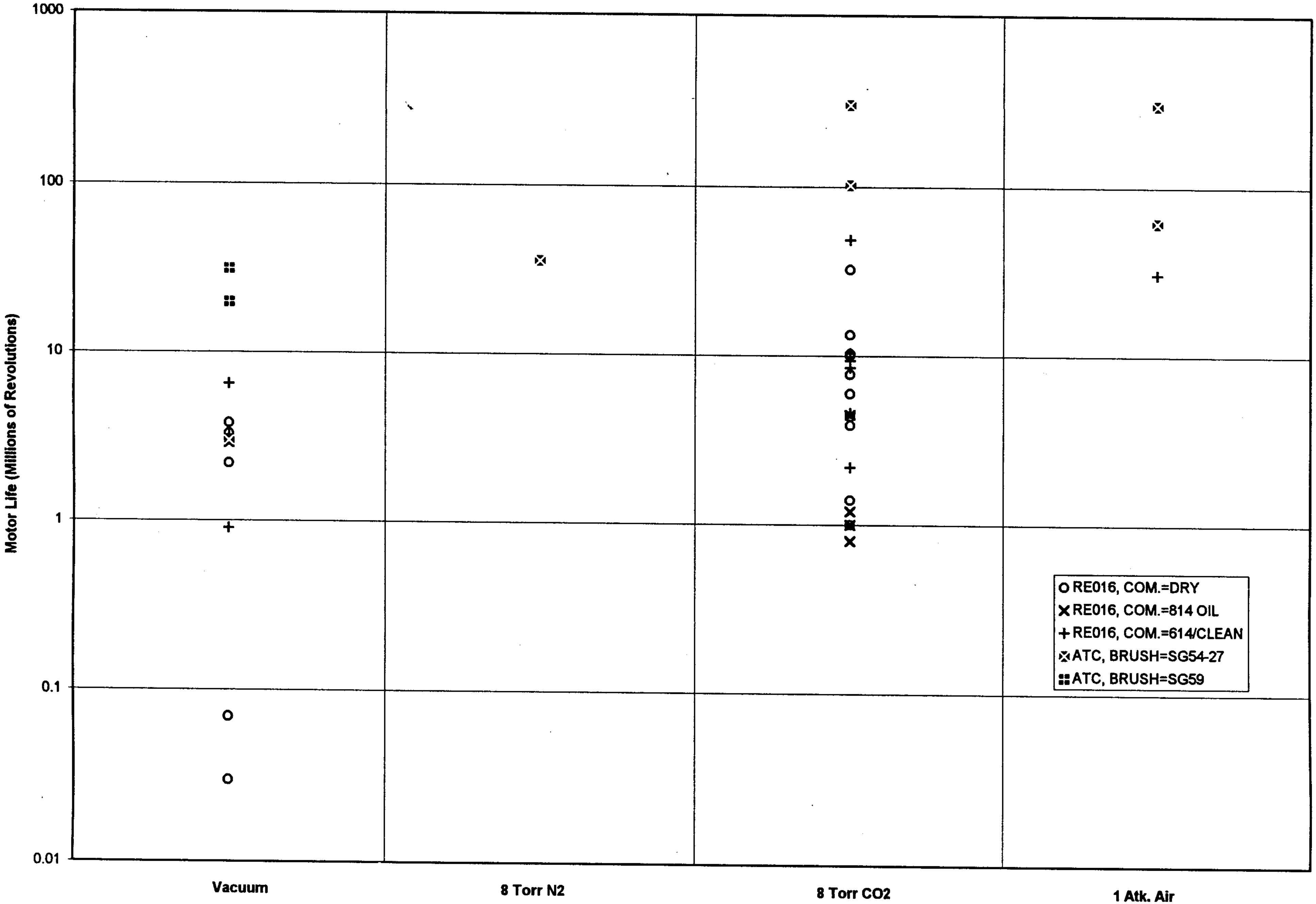

Figure 2. Motor Life vs. Atmosphere

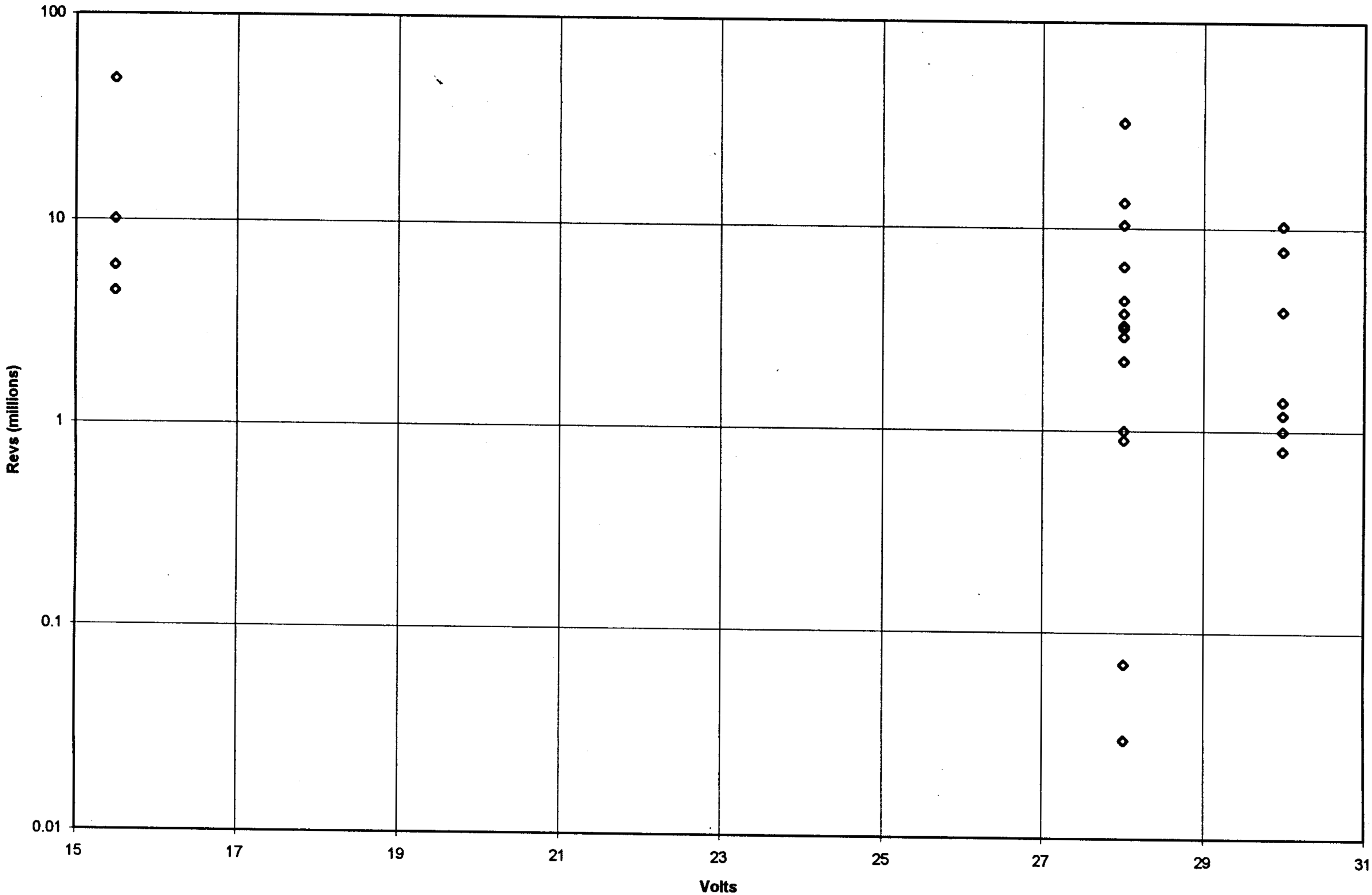

Figure 3. Maxon RE016 Motor Life vs. Voltage

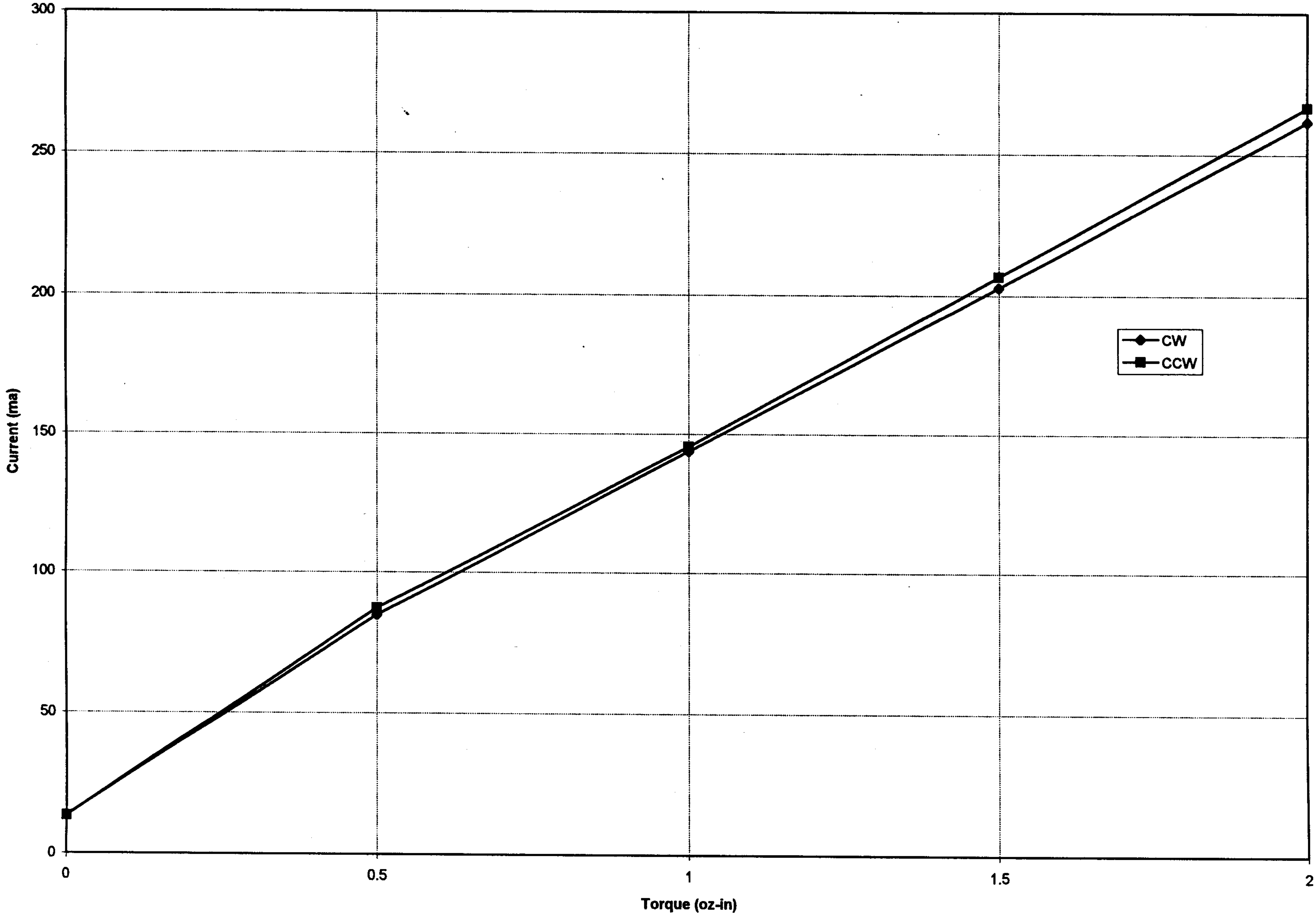

Figure 4. ATC Motor S/N 0039 Current vs. Torque @ 28 Volts

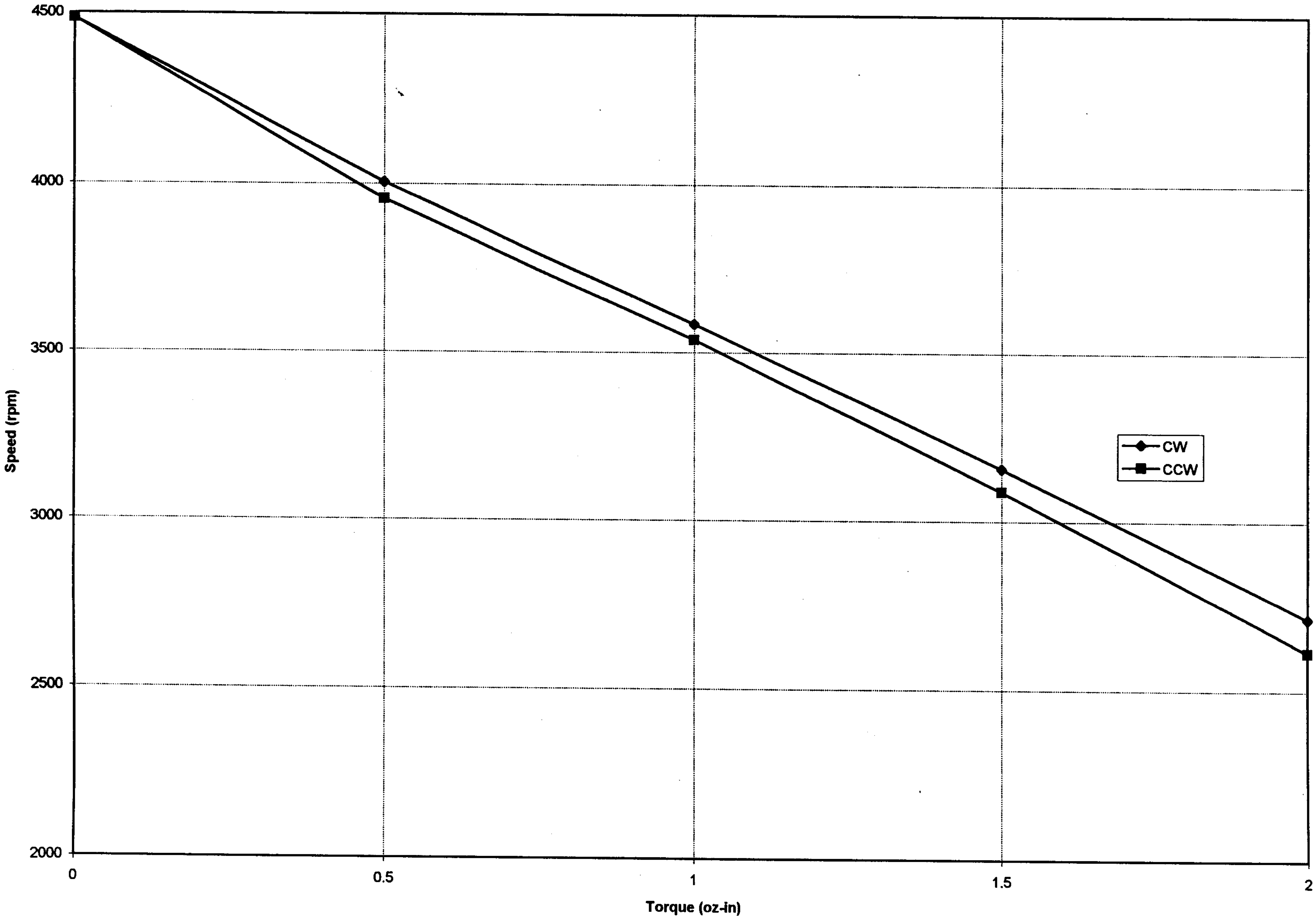

Figure 5. ATC Motor S/N 0039 Speed vs. Torque @ 28 Volts